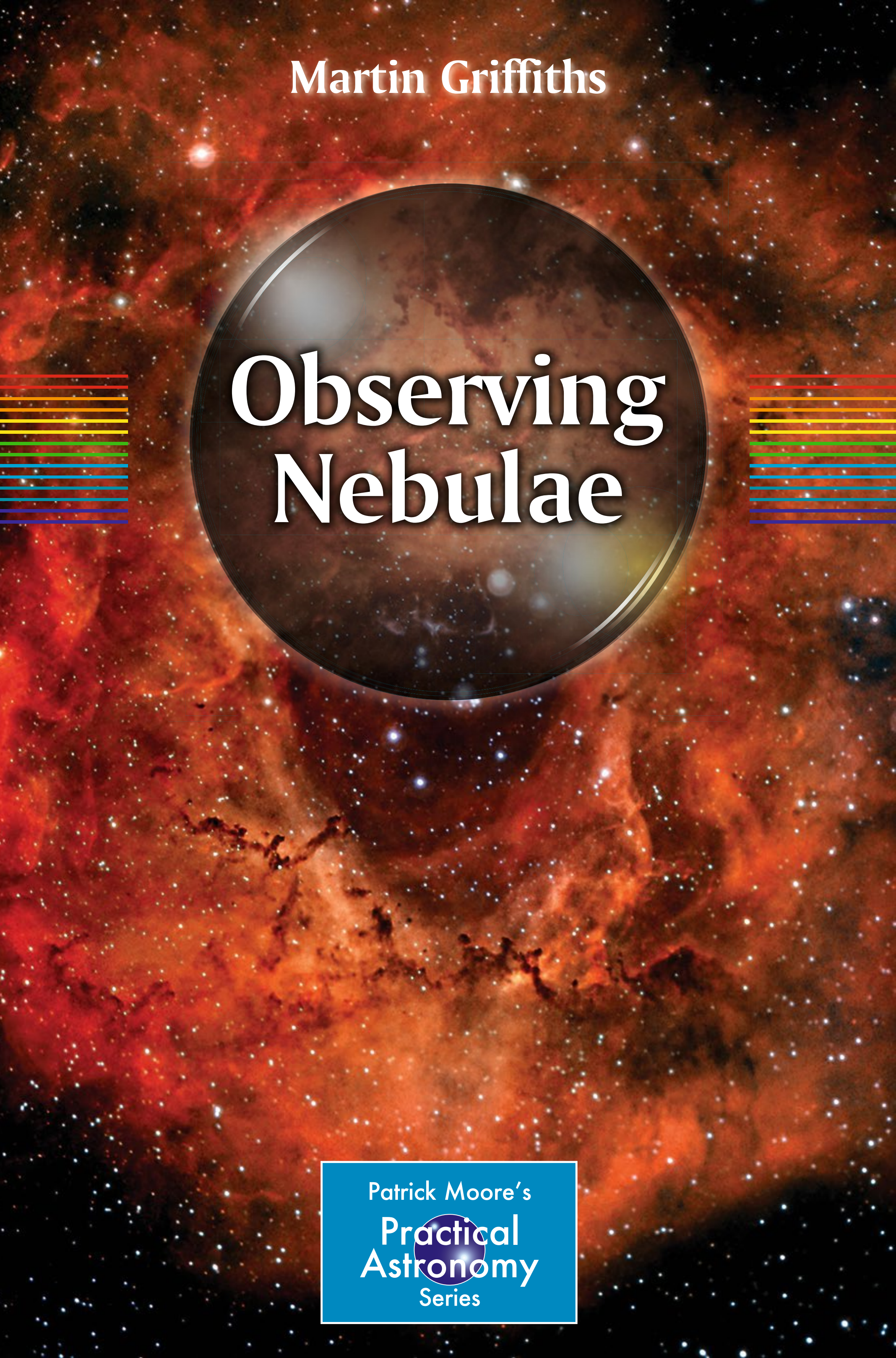
Martin Griffiths

Observing Nebulae



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Messier 8 and Messier 20. Image by Martin Griffiths

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Martin Griffiths
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This book is dedicated to:
My wonderful wife Dena
For all her patience and support. You are my brightest star….

About the Author

Martin Griffiths is an enthusiastic science communicator, writer, and professional astronomer. Over his career he has utilized history, astronomy, and science fiction as tools to encourage greater public understanding of science. He is a recipient of the Astrobiology Society of Britain's Public Outreach Award (2008) and the Astronomical League's Outreach Master Award (2010). He also holds the League's Master Observer certificate and has written or contributed to over 100 published science articles for many journals.

He was one of the founder members of NASA's Astrobiology Institute Science Communication Group, which was active in 2003–2006. He also managed a multimillion pound European program in Astrobiology for adult learners across Wales in 2003–2008. Since then he has been involved in promoting adult education across Wales, and after spending 17 years as a lecturer at the University of South Wales he is now Director of the Brecon Beacons Observatory and a science presenter and consultant for Dark Sky Wales. As a consultant to the Welsh government through his involvement with the Dark Sky Discovery initiative, he enables public access to dark sky sites in association with Dark Sky Wales, Dark Sky Scotland, and Natural England. He was also responsible for surveying the sky quality of the Brecon Beacons National Park for their successful bid to gain International Dark Sky Association Dark Sky Reserve status in 2013. He has recently been invited to sit on the steering committee for the Snowdonia Dark Sky Park. Martin has spent many years directing stargazing events at the park and in the last 3 years has provided training for the BBNPA dark sky ambassadors in dark sky related business matters on behalf of the park.

Martin is a Fellow of the Royal Astronomical Society; a Fellow of the Higher Education Academy; and a member of the Astrobiology Society of Britain, the European Society for the History of Science: the British Astronomical Association, the British Science Association, the Webb Deep-Sky Society, the Society for Popular Astronomy, and the Astronomical League. He is also a local representative for the BAA Commission for Dark Skies.

Preface

Nebulae are among the most abundant objects for amateur astronomical study and are very rewarding to photograph. A bright nebula can be counted as one of the most inspiring sights nature has to offer, and nebulae are very diverse, with a wide range of sizes, magnitudes, and availability to small telescopes. Nebulae are fascinating, beautiful, and enchanting; what could be more wonderful than contemplating these celestial objects, watching a snapshot in time of stars being born, imagining the emergence of planetary systems, and even in some mature nebulae perhaps the bombardment of surfaces that may become conducive to life? Their ethereal nature, short lifetime, and range of forms make observing nebulae a pleasing study.

I have been an astronomer from a young age and have been captivated by many objects that have become personal favorites; as with most other astronomers, one returns time and again to old familiar ones no matter how often they have been examined in the past. Nebulae are a constant source of fascination and study, and almost every time I photograph them they seem to display some new detail or shade that I may have missed before. The change in sky conditions and transparency adds to the fervor of tracking down some faint objects, and challenging oneself to find some faint beauty is always greatly affecting.

I have set this book out in a format that will hopefully enable the novice to pick up the information and go with it into the observing field. I do not expect everyone to engage with the astrophysical concepts included, although learning about such adds stimulus to the search for nebulae, as I believe that a good understanding of the processes involved can add to the observing experience when one is struggling to find some faint or elusive object to add to one's observing list. The thrill of individual discovery is often augmented, I find, by understanding the phenomenon behind the object that one is observing.

I hope that this volume will provide the tools necessary to start searching for these wonderful entities. It does not matter what the aperture of your telescope is or how frequently you observe. There are many bright (and dark!) objects included in this book to please and delight most observers, and hopefully the illustrations will satisfy an armchair astronomer. I have attempted to strike a balance between easily visible objects that can be seen in any telescope or binoculars and nebulae that are a direct challenge to those with large aperture equipment.

I have also attempted to provide an historical and physical analysis of nebulae in order that the reader has a ready volume covering both observational and astrophysical aspects of the subject, which will give added understanding and impetus to any search. I find that when teaching students the ability to see a faint or fuzzy blob of light is augmented by the fuller physical understanding of its intrinsic nature, leading to a greater appreciation for the object. How often have we shown someone a celestial delight we consider significant, only to have that observer disparage the eyepiece view? Observing any deep sky object with relatively small telescopes is not going to reveal a professional, observatory quality image, but this lack can be turned to our advantage by imparting some foreground knowledge on the inherent nature of the item viewed, enabling an appreciation of cosmic distance, scale, and power from our fleeting Earthly platform.

In the final analysis, I want observers to enjoy their experiences in hunting down these wonderful nebulae and discovering them for themselves. I hope this small book will help one to grow in knowledge and appreciation of one striking facet of the universe around us.

Glyntaff, UK
2016

Martin Griffiths

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Unless otherwise acknowledged in the text, all photographs have been taken by the author from either the Griffon Educational Observatory in Andalucia, Spain, or the Brecon Beacons Observatory in south Wales, UK, and are the author's copyright as are the images of the LCOGT and Faulkes telescope archive and those of Allan Trow, Nick Howes, and Andy Burns.

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Chapter 1

Nebulae in History

We do not know the name of the first human who contemplated the stars; indeed they may not have been human in the sense that we think of today in the form of Homo sapiens sapiens but may have been one of our remote ancestors such as Homo ergaster, Homo heidelbergensis or even our cousins Homo neanderthalis. Nevertheless, the heavens as we understand them today are a work of our human family and a projection of our thoughts, desires and accomplishments. Into the band of fixed stars was added the rather ambiguous term “nebulae,” which is merely the Latin term for “cloud,” and several objects may well have looked a little cloudy to ancient observers under the pristine skies of a non-polluted environment.

Possibly the most pervasive and inspiring “nebula” is the Milky Way, our home galaxy with its countless star clouds and knotty condensations matched only by the dark inclusions of molecular clouds that cross its face. However, the Milky Way is not a nebula in the true sense. For the purposes of this book, we shall define true nebulae as those objects that are composed of dust and gases and not galaxies, star clusters or unresolved stars, asterisms or stars as individual entities.

Nebulae in Ancient Times

The star clusters Pleaides and Hyades in Taurus have been known since classical times and indeed were even recorded in common stories and literature by such writers as Homer in the *Iliad* in the eighteenth century BCE and Hesiod in his tract *Works and Days* around 740 BCE. The Pleiades are also mentioned in the Bible by Moses, who is commonly ascribed the authorship of the *Book of Job*, possibly written even earlier than Hesiod or Homer. In Babylonian sources and inscriptions

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mention can be found to such objects as the Orion Nebula or even the Andromeda Nebula, but the true nature of these things was not known to the ancients, and this is part of the problem; anything unresolved or cloudy-looking became a nebula, and it was difficult for astronomers in later times to separate out the true nature of the objects themselves.

Aristotle observed the open star cluster Messier 41 in Canis Major around 325 BCE; this observation would make this cluster the faintest object reported in ancient times. A few years later, around 300 BCE, the poet Aratos mentions Messier 44, the Beehive Cluster, as a cloudy patch in Cancer in his book *Heavenly Phenomena* (*Phainomeina*). Over 150 years later, between 146 and 127 BCE, the astronomer Hipparchus of Rhodes observed the fixed stars and compiled a catalog that would be used for centuries. This catalog mentioned just two nebulous objects, one of which, the "sword handle" in Perseus, had not been mentioned before in classical literature.

In the ancient world, however, the book that survived and was used for almost one and a half millennia afterward was the *Almagest* by the Alexandrian astronomer Claudius Ptolemy. This text included seven nebulous objects, three of which were starry asterisms but not physically related objects. Two were taken from Hipparchus's existing catalog of fixed stars, and two were new. One is now known colloquially as Ptolemy's Cluster and is the star cluster recorded as Messier 7, and the other makes up most of the constellation of Coma Berenices, the star cluster Melotte 111. However, it must be emphasized that these are not nebulae in the true sense of the word; in pre-telescopic times these were unresolved clusters of stars, not collections of gas and dust.

Post-Classical Discoveries

The first really "nebulous" object to be discovered and documented was the Andromeda Galaxy, observed around A. D. 905 and documented around A. D. 964 by the Persian astronomer Al Sufi in his *Book of Fixed Stars*. Sufi also mentions a nebulous star little more than 2° north of Omicron Velorum, which is probably the open cluster IC 2391, just visible to the naked eye. He also includes six of Ptolemy's objects, and a new asterism in Vulpecula (actually Collinder 399, also nicknamed the Coathanger Cluster) and mentions the Large Magellanic Cloud as visible from southern Arabia, so his work includes a total of nine entries (Fig. 1.1).

The nature of some nebulous objects changed when the Portuguese sailor Vicente Pinzon reported the "Coal Sack" Nebula in Crucis as his ship journeyed southward, though it was Peter Martyr who first gave a formal description of the Coal Sack around 1521. Just 2 years previously Ferdinand Magellan had reported the sighting of two nebulae that now bear his name—the large and small Magellanic clouds. The famed navigator Amerigo Vespucci commented during his third voyage on the large and small Magellanic clouds, but by this time they were not new discoveries.

Fig. 1.1 Al-Sufi's depiction of the Andromeda Nebula

The first person to recognize and discover a nebula in the true sense of a gaseous cloud was Nicholas de Peiresc, who saw the Orion Nebula in 1610. It is notable that it is also the first deep sky object ever discovered with a telescope, though Galileo did note that the Beehive Cluster in Cancer could be resolved into stars—not a true nebula in any sense, although he did look at the Orion Nebula without noticing a gaseous component. That the true nature of nebulae was still a mystery and not identified as gaseous clouds can be seen from the claim of Simon Marius on his discovery of the Andromeda Galaxy in 1612. Marius was the first person in the west to record the object. Again, this is not a nebula in the sense that will be used in this book.

Due to the plethora of nebulae being discovered with the telescope, a new catalog of objects was produced by Giovanni Hodierna, who was astronomer at the court of the Duke of Montechiaro. This was exclusively a catalog dedicated to nebulous objects, and his list contains 40 entries, including 19 real nebulous objects, found with a simple refractor. It was first printed in Palermo in 1654, and included within it are independent discoveries of the Andromeda Galaxy and the Orion nebulae, Collinder 399, the alpha Persei moving group and a real nebula, that of the Lagoon Nebula, or Messier 8, in Sagittarius.

Hodierna’s catalog fired the imaginations of astronomers of the seventeenth century, and soon catalogs containing new entries were published that included improved star charts such as Johannes Hevelius 1689 catalogs *Prodomus Astronomiae*, and *Uranographia*. Hevelius included a total of 16 nebulous stars, two of which are actual objects (the Andromeda nebulae and Messier 44) while the other 14 are asterisms or non-existent. Hevelius is also claimed to be one of the first to have seen Messier 22 in Sagittarius, but this discovery was made by Abraham Ihle around 1665. Again, the true nature of nebulae was difficult to separate out into the proper context.

The Eighteenth Century

The tempo of observation and discoveries shifted from the continent to Great Britain with the publication of *Historia Coelestis Britannica* in 1712 by John Flamsteed, the first Astronomer Royal. Flamsteed refers to several “nebulae” and “nebulous stars,” though this included objects already known such as Messier 31, Messier 42, the Coma Cluster Melotte 111 and the sword handle in Perseus. He did see the Rosette Nebula, NGC 2237, and drew attention to the star 12 Monocerotis inside it, but his telescope was not large enough to make out the gaseous ring of materials in the vicinity.

Three years later, Edmond Halley published a list of six luminous spots in the *Philosophical Transactions* of the Royal Society. Halley's rather small list was the second catalog of deep sky objects after Hodierna's, though it was ironically the first to become widely known.

The French astronomer Jean Jacques De Mairan discovered a nebulous patch around a star north of the Orion Nebula, which is now accorded his name and is also known as Messier 43. This true nebula was shortly followed by another when John Bevis discovered the Crab Nebula, Messier 1, and included it in his star atlas *Uranographia Britannica*, completed in 1750. Around the same time the first star charts commercially available were being published by John Senex of London, and in their upgrades some nebulae were included by the Welsh astronomer, cartographer and Assay master at the Royal Mint, Joseph Harris.

The problem of seeing nebulae properly can be illustrated by the paper of William Derham, who published a list of sixteen nebulous objects in the *Philosophical Transactions* of the Royal Society in 1733. Fourteen of these entries were taken from Hevelius's catalog and the other two from Halley's list. However, only two of the objects were real, Messier 31 and Messier 7; all the others were copies of previous mistakes, being either nonexistent or mere asterisms.

About in 1746, Phillipe de Cheseaux compiled a catalog of the positions of several clusters and what he called "nebulous stars," which included the true nebula Messier 17. De Chéseaux's list was given to the French Academy of Sciences in 1746, but it was not published until the following century, by which time many other true nebulae had been added to observing lists. Another French observer, Guillaume de Gentil, discovered the companion galaxy to the Andromeda Nebula in 1749. Le Gentil also described both cluster and the gaseous nebula in M8 that same year but did not draw a distinction between each object, as all were still lumped under the epithet of "nebulae" no matter what their true identity.

Most observations were made from the northern hemisphere, so much was expected of potential discoveries made by Nicholas de la Caille when he sailed to southern Africa in 1751. Here he compiled a catalog of stars and deep-sky objects and also invented several southern constellations. His catalog contained 24 original entries and two independent rediscoveries. These discoveries include the vast Tarantula Nebula, NGC 2070, in the Large Magellanic Cloud. Another nebula, the spiral galaxy Messier 83, became the first galaxy beyond the Local Group to be discovered but again was not a nebula in the true sense of its use here, and its real nature remained unknown until the twentieth century.

De la Caille also introduced the first separation of nebulae into classes when he produced the following categories:

1. Nebulae
2. Nebulous star clusters
3. Nebulous stars

It was a brave attempt, but it did not really get to the true nature of the nebulae at all.

Following on from these discoveries was the compilation of the catalog of "objects to avoid while looking for comets" by the French astronomer Charles Messier in 1771. For more than a decade Messier was alone in looking for clusters and nebulous objects, but during that time he discovered 27 objects and in later editions of his catalog he observed 18 more nebulous objects and put the true nature of nebulae at the forefront of astronomical discussion. He also drew them as accurately as possible, and some of these drawings hint at the gaseous nature of nebulae as can be seen in Fig. 1.2 here—Messier's depiction of the Orion complex.

While Messier compiled his observations, other observers were also adding to the tally of nebulous objects in the sky. Antoine Darquier discovered the Ring Nebula, Messier 57, shortly before Messier, though they both found it when observing the

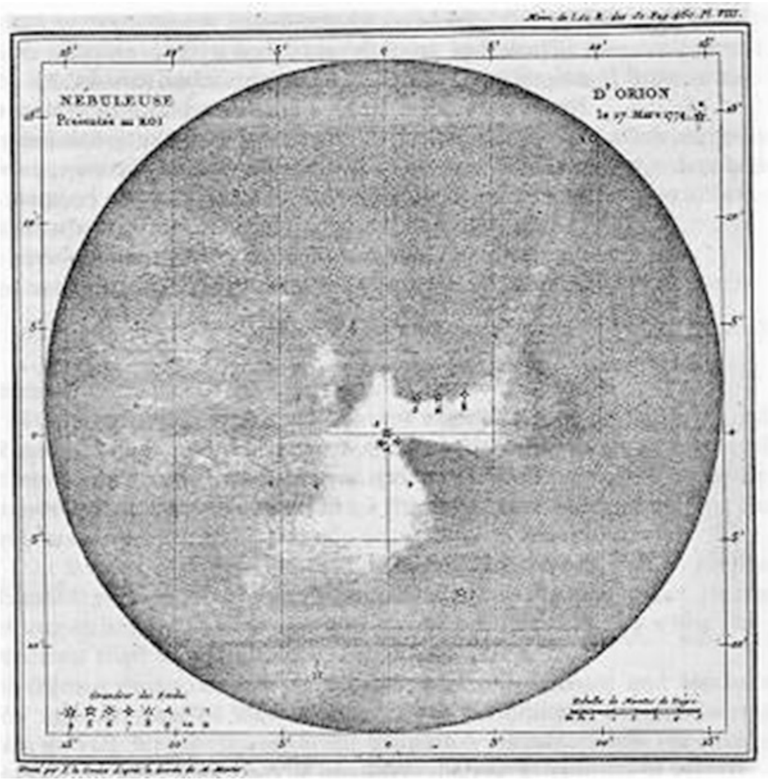

Fig. 1.2 The Orion Nebula by Messier

path of a comet discovered in 1779 by Johann Bode. Messier's friend Pierre Mechain discovered about 25 objects, most of which he contributed to Messier's catalog, but many of these discoveries are now known to be galaxies. The Messier catalog eventually became a huge contribution to the search for nebulae, even if it did not address their physical characteristics in total. Overall it contained almost every nebulous object known at the time, and today it is known to include planetary nebulae, gaseous nebulae, reflection nebulae and of course the first supernova remnant ever discovered, Messier 1. Such a list was bound to impress the German-British astronomer William Herschel, who received a copy of Messier's updated catalog in 1781. Herschel eventually went to Paris to meet Messier. The catalog had a profound effect on this wily observer of the heavens.

The Contribution of the Herschels

Possibly the greatest of all visual telescopic observers of the eighteenth century and famous because of his discovery of planet Uranus in 1781, Herschel set out to sweep the heavens and improve upon Messier's catalog. Herschel owned the largest telescopes in use at the time and so started a systematic survey of the heavens first from Datchet and then from Slough in England with large telescopes of up to a 48-inch aperture. Eventually publishing his catalog in three volumes, Herschel cataloged over 2500 discoveries and was assisted in his surveys by his sister Caroline, who became the world's first professional female astronomer.

To make sense of the amazing amount of discoveries during his sweeps of the British sky, Herschel produced a system that was based on his observations at the eyepiece. He defined eight groups of nebulae. They are:

1. Bright nebulae
2. Faint nebulae
3. Very faint nebulae
4. Planetary nebulae
5. Very large nebulae
6. Very compressed and rich star clusters
7. Compressed clusters of small and large stars
8. Coarsely scattered clusters of stars

As the true nature of the objects was unknown at that time, this classification seems rather arbitrary and insufficient to gain much useful information from. Nevertheless, it was the first important study of the location and appearance of nebulae in a strict astronomical sense.

Both William and Caroline exhausted object discoveries in the northern skies by around 1800. However, the southern sky was still waiting to be explored and swept systematically in the same way that William had done in Britain. To this end the astronomer James Dunlop went to New South Wales, Australia, in 1821, accompanying Sir Thomas Brisbane and set up a small but well-equipped observatory. Dunlop eventually became the director of the Brisbane observatory at Paramatta, and between 1823 and 1827 he compiled the *Brisbane Catalog* of over 7000 southern stars. His inclusion of deep-sky objects became the *Catalogue of Nebulae and Clusters of Stars in the Southern Hemisphere* and contained 629 entries.

This catalog was presented to the Royal Society in 1827 by William Herschel's son John Herschel, and Dunlop was awarded the gold medal of the Royal Society for his pioneering work. Disappointingly, many of Dunlop's objects proved to be nonexistent, or so badly described that they could not be identified, and only half of his entries could be related to real objects. This led to John Herschel traveling to Feldhausen in Cape Town, South Africa, to continue his father's work in extending deep-sky catalogs to the southern sky and checking on Dunlop's work.

John Herschel had already added about 525 new entries to his father's northern catalogs and now wanted to do the same for the southern hemisphere objects. Between 1833 and 1836 he intensively studied the southern skies, and by 1847 he had published a catalog containing an impressive 1713 entries. John later fused his father's catalogs and his southern ones into a single volume with the publication of the *General Catalogue of Nebulae and Star Clusters*, which contained over 5000 separate objects. This catalog was extended by J. L. E. Dreyer at Armagh Observatory in Ireland in 1888 to become the *New General Catalogue* and its supplement the *Index Catalogue*, both of which of are still the standard reference works for deep-sky objects.

The contribution of the Herschel family finally brought the great era of deep-sky discoveries to an end as far as visual observing was concerned. The new tools of spectroscopy and especially photography began to take over, and the true nature of nebulae as regions of gaseous material as opposed to unresolved stars or galaxies was revealed by these new tools. Indeed, the true nature of nebulae was discovered by the British pioneer of spectroscopy, William Huggins, in the 1860s, while in the 1920s the true nature of galaxies as independent Milky Ways became apparent thanks to the work of Edwin Hubble. Nebulae in various catalogs could now be separated into their true groups, and astronomers recognized emission nebulae, reflection nebulae, planetary nebulae and a new group of objects, the dark nebulae.

Dark Nebulae

Although dark areas in the heavens had been noted by Herschel and other astronomers, it was the work of Edward Emerson Barnard that brought them to prominence. His father having died before he was born, Barnard was raised by his mother in abject poverty. At the age of eight he was apprenticed to a photographer's studio, where part of his job entailed making prints, getting to know the basics of the photographic processes then in use and using a large camera to keep track of the Sun. It was during such long periods of manually moving the camera that he gained the experience necessary to guide the telescopes and camera he would use in later life.

By the time he was 17 he began to teach himself astronomy with the aid of a book that was left to him by a family member. Shortly afterward he built his own telescope and studied the sky intently before purchasing a good quality 120-mm refractor. From then on Barnard's life improved dramatically. He discovered two comets in a short time, and despite having no formal education, he was hired as an astronomer and observer by Vanderbilt University, who also enrolled him as a student and paid his fees by scholarship.

His few years at Vanderbilt were very fruitful. He discovered ten comets and made a reputation for himself as a talented observer. Despite his photographic background most telescopes still relied on human observation rather than the slow photographic processes then in use. In 1887 the new Lick Observatory at San Jose hired Barnard, and although it was here that he visually discovered the fifth moon of Jupiter (Amalthea), he did not get on personally with Lick's director, and he looked for an opening as an astronomer elsewhere. Ironically, his discovery of Amalthea would be the last visual discovery of a Solar System object by an astronomer as the new process of photography gained ground. Barnard was very involved with this new photographic revolution and its application to astronomy, as it was while he was employed at Lick that he began the photographic experimentation and guiding that was to become his métier. Barnard proved the power and efficiency of the new process by discovering a new comet on photographic plates shortly after implementing astrophotography at Lick Observatory.

Eventually leaving Lick despite his success there, Barnard went to Yerkes Observatory in 1895 but was disappointed to find that the weather in Wisconsin was not conducive to long exposures or provided many clear nights. Nonetheless, with his companion Max Wolf, he took a keen interest in photographing the Milky Way while at Yerkes, and his patience and endurance paid off in a series of beautiful exposures that stretched him mentally and physically taking guided exposures ranging in periods of 2–5 h; these required superhuman concentration but did reveal star fields with many dark holes and lanes. He came to the conclusion that it was non-illuminated gas and dust that obscured the light of objects behind and began a systematic survey of these features by means of photography of the Milky Way. The dark nebulae had been formally identified (Fig. 1.3).

Barnard spent 8 months taking images of the sky at Mount Wilson in California, in preparation for producing a full photographic atlas of the Milky Way that was to include thousands of images taken at Mount Wilson and Yerkes by the patient astronomer. This was a massive undertaking, and he required much help to make it a success. He hired his niece Mary Calvert in 1905 to assist him in this work and in other astronomical work he was carrying out at the observatory. Compiling the photographs took many years and long hours of concentration and decision making concerning using the best photographs available. In 1919, at the end of World War I, Barnard introduced this work by writing a paper for an astrophysical journal entitled "On the Dark Markings of the Sky with a Catalogue of 182 Objects" and introduced dark nebulae to a wide audience. He went on to personally select the best photographs for inclusion in the work for which he is now famous, the *Photographic Atlas of Selected Regions of the Milky Way*. Sadly, Barnard passed away before the final proofs were available, and Mary Calvert did the final production and dedication.

His atlas of dark nebulae is a standard work and contains hundreds of objects, many of which are quite obscure visually, but this book will point the observer in the direction of some of the more obvious and interesting ones in addition to providing activities for observers looking for a different observing challenge.

The Nebulae Revealed

With the advent of spectroscopes and photography, large nebulous areas were revealed as clouds of hydrogen gas and silicate and carbonate dust within the Milky Way. It was John Herschel who made the supposition midway through the eighteenth

Fig. 1.3 Dark nebulae in Cassiopeia

century that nebulae and star clusters were intimately connected and paraphrased the nebulae as being the "chaotic material of future suns," a term that turned out to be very prescient.

However, it was the great American astronomer Edwin Hubble that finally made the connection between HII regions, dark nebulae, reflection nebulae and the stars that illuminate them in a seminal paper entitled “The Source of Luminosity in Galactic Nebulae,” published in the *Astrophysical Journal* for August 1922 in which he showed that the ionization from bright stars led to the emission lines of the nebulae and supposed that dark nebulae and reflection nebulae were areas of sky where the illumination was coming from stars newly born or, in the case of dark nebulae, were as yet unilluminated as stars were yet to form in them. Later studies in the late 1920s and into the 1930s by Otto Struve, Herman Zanstra, Phillip Keenan and others showed the nature of reflection nebulae in such objects as the Pleiades and the nebulae in Orion, Messier 78.

Today we can understand the connection between the true nebulae and objects of many kinds such as star clusters and individual stars, too. In the next section we shall look in detail at this connection and explore the relationships between clouds of gas and stars, but for those looking for a comprehensive guide to the evolution of deep sky catalogs, the following list should provide some useful information. It is presented here in historical order for clarity.

Historical catalogs—a Quick Guide

Date	Author	Details
134–127 BCE	Hipparchus	Hipparchus includes two nebulous objects in his catalog: Messier 44 and the sword handle in Perseus
A. D.127–151	Claudius Ptolemy	Ptolemy's *Almagest* contains a list of seven nebulae, of which four are actually star clusters: Messier 44, the sword handle from Hipparchus, Messier 7 and Melotte 111
A. D. 964	Al-Sufi	Al Sufi mentions two objects in his *Book of Fixed Stars*: Messier 31 and the star Omicron Velorum. His list contains nine objects, of which six are copies of Ptolemy’s
1590	Tycho Brahe	The Danish nobleman Tycho Brahe completes a catalog of 777 stars from his observatory Uraniborg on the island of Hveen in 1590, containing seven nebulous objects of which only Messier 44 is an actual deep-sky object, the rest being mere asterisms
1654	Giovanni Hodierna	Hodierna publishes a list of around 40 entries, 19 of which correspond to real objects, including an independent re-discovery of Messier 31. The most important object is the true nebula now known as Messier 8
1679	Edmond Halley	Halley includes three nebulous objects in his *Catalog of Southern Stars*: Messier 7, NGC 5139 and NGC 6231, none of which are nebulae in the form of clouds of gas

(continued)

Date	Author	Details
1690	Johannes Hevelius	Hevelius includes 16 new entries in his catalog, including Messier 31 and Messier 44, but all of them are asterisms or known objects without true nebulous features
1712	John Flamsteed	Britain's first Astronomer Royal, John Flamsteed, refers to several nebulae and nebulous stars in the catalog *Historia Coelestis Britannica*. The only one of note is his discovery of the star 12 Monocerotis and the potential of the Rosette Nebula
1715	Edmond Halley	Halley publishes a list of six objects, none of which are true nebulae apart from the already known Orion Nebula
1733	William Derham	Derham publishes a list of 16 objects, but most are asterisms or faint stars
1746	Phillipe de Cheseaux	De Chéseaux compiles a list of 21 nebulae, eight of which are original discoveries; the list includes the true nebula Messier 17 and the Omega Nebula
1755	Nicholas de la Caille	Nicholas de la Caille publishes his catalog of southern deep-sky objects containing 42 entries; a quarter of the catalog entries are erroneous, but 33 are real objects that appear in the *Memoirs* of the French Royal Academy. La Caille classifies these objects according to their appearance in his telescope in three classes
1771	Charles Messier	Messier publishes the first version of his catalog in the *Memoirs* of the Royal Academy of France. Many entries are objects that are already well known such as M42, M43, M44 and M45
1777	Johann Bode	Messier updates his catalog in the *Memoirs* of the Royal Academy of France
1778	Gottfried Koehler	Koehler sends Bode a list of 20 objects for publication in the *Astronomisches Jahrbuch*, which was first published in 1779
1780	Charles Messier	Messier publishes another updated version of his catalog, which now includes 68 objects
1781	Charles Messier	Messier publishes the final version of his catalog in the *Connoissance des Temps* in 1784. Pierre Mechain continues to send Messier observations to add, and in the twentieth century the total number of objects in the catalog is completed at 110
1782	Johann Bode	Bode brings out his *Vorstellung der Gestirne*, adding to his existing list and bringing 110 objects into his star catalog
1789	William Herschel	In the greatest search of the sky in this period, William Herschel produces the most comprehensive catalog of 2500 objects in the *Philosophical Transactions* of the Royal Society. Herschel divides his entries in object classes, but his classes are more descriptive than useful

(continued)

Date	Author	Details
1827	James Dunlop	*A Catalogue of Nebulae and Clusters of Stars in the Southern Hemisphere Observed in New South Wales* becomes the first truly comprehensive survey of the southern sky, but unfortunately many errors creep in. John Herschel study Dunlop's catalog and can only identify 211 of them
1833	John Herschel	John publishes a catalog of nebulous objects observed from Great Britain containing about 525 newly discovered objects, including many of his father's and those of Messier's known at the time
1847	John Herschel	The Cape of Good Hope observations is published in *Results of Astronomical Observations made during the years 1834*, *5*, *6*, *7*, *8 at the Cape of Good Hope*, *being a completion of a telescopic survey of the whole surface of the visible heavens commenced in 1825*. Containing 1713 entries, this catalog was one of the most systematic surveys of the southern sky until recent times
1864	John Herschel	The combined work of the northern and southern hemisphere surveys, the *General Catalogue of Nebulae and Clusters of Stars* appears in the *Philosophical Transactions* of the Royal Society and are mostly ordered by right ascension
1877	J. L. E. Dreyer	This catalog is produced as a supplement to John Herschel's *General Catalogue of Nebulae and Clusters of Stars*. It becomes the forerunner for the next entry
1888	J. L. E. Dreyer	The bedrock of astronomical catalogs today, the *New General Catalogue of Nebulae and Clusters of Stars* is published in the *Memoirs of the Royal Astronomical Society*
1895	J. L. E. Dreyer	The *Index Catalog of Nebulae Found in the Years 1888–1894*, *with Notes and Corrections to the New General Catalogue*, is published in the *Memoirs of the Royal Astronomical Society*, and is the first such catalog beyond the *NGC* created by Dreyer
1908	J. L. E. Dreyer	The second *Index Catalogue* or the *Second Index Catalogue of Nebulae Found in the Years 1895–1907*; *with Notes and Corrections to the New General Catalogue and to the Index Catalogue for 1888–1894*, is published in the *Memoirs of the Royal Astronomical Society* This was one of the final "great catalogs" of nebulae made by visual astronomers but now included the results of photographic surveys of the sky
1927	E. E. Barnard	The *Barnard Catalogue of Dark Markings in the Sky* lists the dark nebulae of the Milky Way in two versions, which are completed by 1927. The catalog contains photographs of 369 objects

(continued)

Date	Author	Details
1959	Stewart Sharpless	Compiled in 1959 by the American astronomer Stewart Sharpless, this is a list of 313 HII regions of varied magnitude and size that has become a favorite with astrophotographers. Many of these objects overlap with the *Messier*, *NGC* and *IC* catalogs, as they were compiled from Palomar Sky Survey plates and from H-alpha photographs taken at Flagstaff Observatory
1965	Beverley Lynds	*Lynds Catalogue of Bright Nebulae* is produced, a compilation of 1125 true nebulae taken from various sources, including the Palomar sky survey and earlier catalogs

Chapter 2

The Astrophysics of Nebulae

Stars experience stages of birth, growth, middle and old age and finally death. Astronomers talk of these stages as progressive stellar evolution, although the process bears no resemblance to the biological theory of evolution proposed by Darwin. They begin with nebulae and generally end with a nebula, either a planetary nebula or the expanding mass of a supernova explosion. Stars are the only entities in our universe that follow the strict rule of evolution, slow change with time, but they remain stars, of course, for the majority of their lives.

The ancients always thought of the stars as immutable, changeless and fixed in the heavens. Nothing could be further from the truth, however, as stars undergo many alterations during their lifetimes, with none as dramatic as the changes wrought at birth.

The birth of stars is shrouded, not so much in mystery but by the clouds that they are born out of. These clouds are visible as dark nebulae along the spine of the Milky Way and are the nurseries of stars yet to come. Stellar birth is a process hidden in darkness, and it is only with advances in infrared, radio and short wavelength astronomy that we have been able to see increasing detail in such clouds and add to our knowledge of star birth.

One of the most useful tools enabling astronomers to make predictions of stellar evolution is the Hertzsprung-Russell diagram. From an observational point of view, just a few parameters need to be met to place any star on the HR diagram and so enable an examination of the timelines of birth, lives and deaths—the lives of stars from cradle to grave, so to speak. The HR diagram is a superb diagnostic device that, once married with astrophysical equations, allows astronomers to extrapolate forward to examine the end products of stars, but more importantly for the purposes of this study, to engineer a reverse understanding and discover how stars of particular masses are born and make detailed predictions that fit them within the diagram boundaries.

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Features such as color relate to temperature, and so both of these are included in the diagram as are the luminosity in comparison to the Sun and the absolute magnitude of any star. These can be obtained by distance modulus calculations so that the real luminosity of stars can be gauged and the placement of a body on the diagram as accurate as possible. An example of a HR diagram is included here for the reader to digest (Fig. 2.1).

The use of the diagram in charting the birth of stars will become obvious later. Suffice it to say for now that stars will live out the main phase of their lives converting hydrogen into helium on the main sequence of the diagram. However, before they become stars, they have to form from nebulous clouds of materials in space, and we shall now examine this concept in more detail.

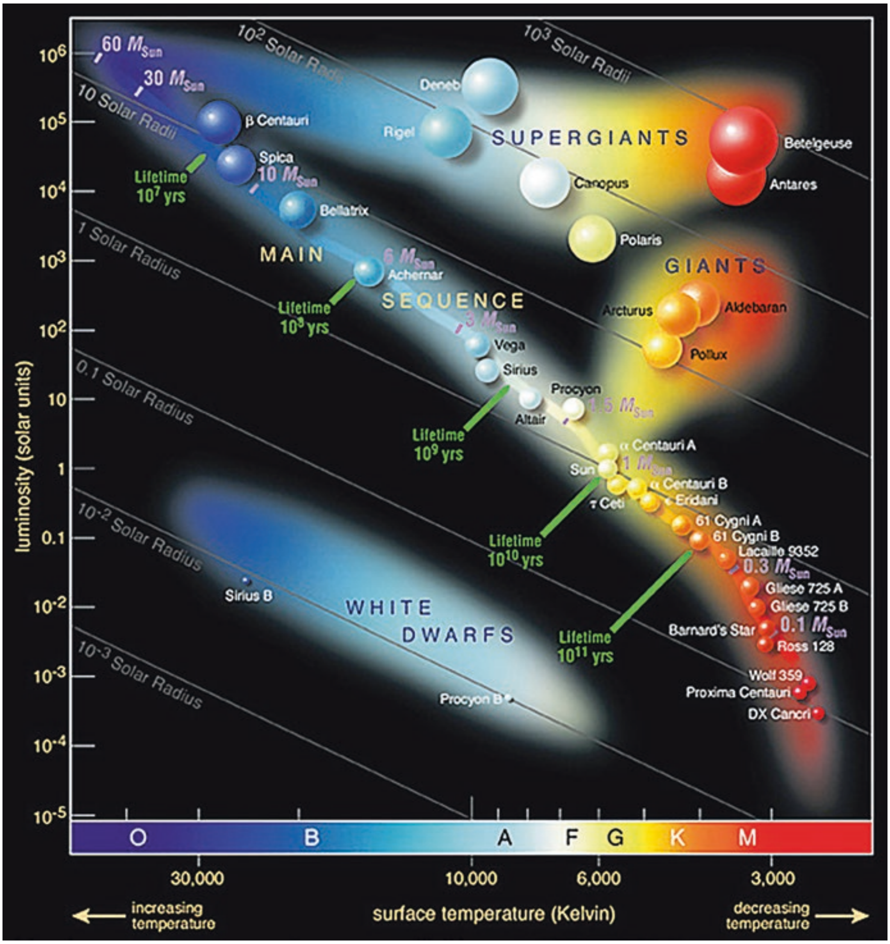

Fig. 2.1 The Hertzsprung Russell diagram (From Wiki Commons; https://upload.wikimedia.org/wikipedia/commons/1/17/Hertzsprung-Russel_StarData.png)

The Interstellar Medium

It is not difficult to get the impression that the space between the stars contains absolutely nothing at all, but in fact this could not be further from the truth. The spaces between the stars contain the gas and dust of the interstellar medium (ISM), the future materials of suns and planets. Though this material is thinly spread it is abundant enough due to the vast size of space to form an appreciable mass along our line of sight and extinguish stars in the far distance by absorption of starlight.

However, this material is not always evenly spread across space, and local condensations into vast molecular clouds or knotty dark globules can be seen in certain areas of the sky. Generally speaking, the ISM is quite vapid, with less than one hundred particles per cubic meter. A dense part of the ISM could even reach 10^{17} particles per meter, which in comparison sounds enormous until one considers that in a single average human breath, there are 10^{24} particles! Another consideration is the temperature differences in the ISM, which can range from just 10 to 1,000,000 K, depending on the material under examination. This substance is basically hydrogen and helium gas with trace amounts of carbon, oxygen and nitrogen as well as other elements of the Periodic Table in very low abundances. The following figure shows the distribution of the ISM in the Milky Way Galaxy and note how the denser areas of the ISM are concentrated along the disk of the galaxy itself (Fig. 2.2).

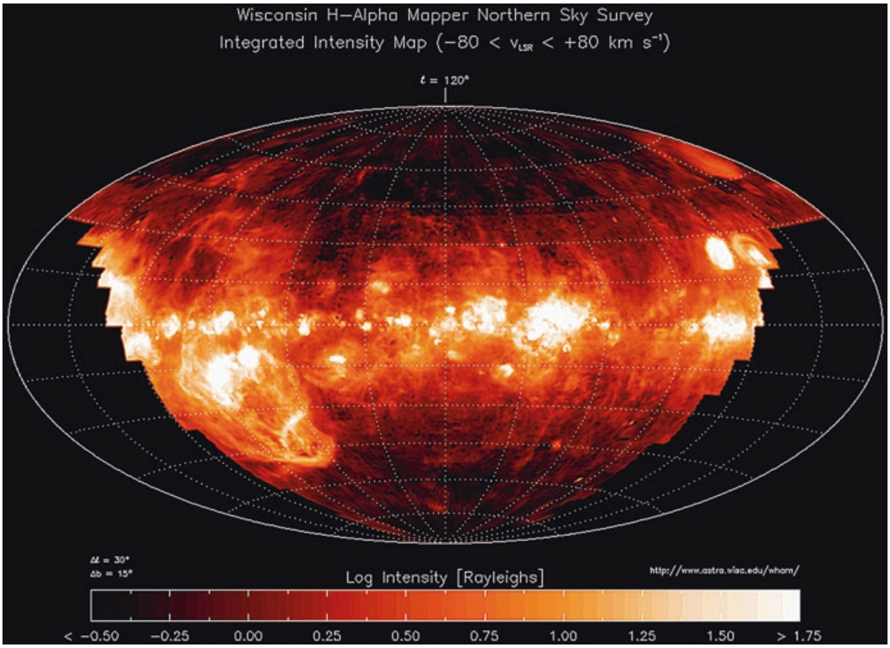

Fig. 2.2 The ISM (Wikki Commons; https://upload.wikimedia.org/wikipedia/commons/f/ff/WHAM_survey.png)

The ISM is mostly accounted for by matter that can be called the intercloud medium, a term that draws a difference between the ISM and denser areas such as molecular clouds. The intercloud medium is mostly constructed from hot gases that are the result of stellar winds and coronal ejections from stars. Included in the intercloud medium are the ejected materials from supernovae and planetary nebulae, and as this material is very sparse, it is possible to observe distant objects through it. Following these low density areas are those of higher density in which potential collapse into new stars can occur or has occurred. These are known as diffuse clouds and dense clouds, while others in this group are known as emission or HII regions; stars have already been born here and are illuminating the nebulae we see.

The following table illustrates the densities and abundances of the different materials that collectively make up the ISM and how astronomers observe them.

Material	Volume (%)	Temperature (K)	Density (M^3)	Hydrogen	Observation
Molecular clouds	<1	10–20	10^2–10^6	Molecular	Radio and IR
Cold neutral medium	1–5	50–100	20–50	Neutral atomic	21 cm radio
Warm neutral medium	10–20	6000–10^4	0.2–0.5	Neutral atomic	21 cm radio
Warm ionized medium	20–50	8000	0.2–0.5	Ionized	Hα emission
HII regions	<1	8000	10^2–10^4	Ionized	Hα emission
Coronal gas or the hot ionized medium	30–70	10^6–10^7	10^{-4}–10^{-2}	Ionized (and ionized metals)	X-rays

Much of the early work on the ISM was developed by Johannes Hartmann around 1904, after he observed the weak sodium lines emanating from delta Orionis apparently being absorbed. He postulated a thin, ether like material lying along our line of sight to the star. His study and those of later astronomers, notably Edward Pickering, using absorption line spectroscopy, put the ISM firmly on the astronomical map; indeed it was Pickering who identified the ISM as a gas rather than the tentative ether idea that was common at the time. Later techniques in IR and radio astronomy have added greatly to our understanding of the ISM and its role in star formation and nebulae production.

However, how does the ISM collapse to form stars in the first place? Why is there still so much of the ISM around if gravitational collapse pulls the materials together?

Cloud Collapse and the Jeans Mass

If it were merely a question of gravity then the ISM might not exist in great quantities today, and the galaxy would be filled with stars in profusion. However, as we can see from the above table, the ISM has a low temperature, which maintains